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13. ABSTRACT (Maximum 200 Words) Engineering the total ship as an integrated system using systems engineering, not merely the physical aggregate of systems designed by disparate organizations, has been recognized as the key to designing and producing these complex entities in an effective and affordable manner. The engineering of the total ship has proven to be difficult to integrate, however, especially since the two main disciplines, naval architecture and combat systems, operate in distinct domains. In addition, the engineering task is becoming ever more of a challenge, now that the 'ship as a system' is being re-defined as 'ship as part of the battlegroup system-of-systems'. The expanded system context forces engineers to deal with complexity as an integral characteristic of the process. This paper presents the impacts associated with engineering the total ship from these two important aspects, the differing design domain perspectives and the redefining of the engineering task as relating to a system-of-systems, and outlines a possible framework to allow a more generalized and rigorous design approach.				
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Functional and Physical Decomposition for Ship Design

ABSTRACT

Systems engineering is recognized as a key to engineering ships in an effective and affordable manner. A new challenge is rising as total ship system boundaries are being re-defined to include new warfighting aspects in the design process. This introduces not only an expansion to new subsystems as part of the process, but adds new complexity to the designer's consideration. This paper discusses the challenges associated with engineering the total ship as part of the joint warfare system from two important aspects, the impact of differing design team perspectives and inherent system complexity.

INTRODUCTION

Systems engineering is recognized as a key to engineering ships in an effective and affordable manner (Leopold, Svendsen, and Kloehn 1982), (Rains 1990), (Reed 1981), (Tibbetts, Keane, and Riggins 1988). Naval engineering has long been the title associated with the system design and engineering of naval warships. "Total ship system engineering" (TSSE) has been recently defined in an attempt to describe this systems view, and provide a framework for ship designer's to follow. Implementation of TSSE has always been complicated due to the need to integrate the working of engineering teams with differing warfare perspectives, principally 'naval architecture' and 'combat systems'. A new challenge is arising as total ship system boundaries are being redefined to include new integrated and joint warfighting aspects in the design process. TSSE concentrates on the ship as the object of design, but this must be done in the context of all the interconnected system aspects external to the ship simultaneously. This introduces not only an expansion to new subsystems as part of the process, but adds new complexity to the designer's consideration. This paper discusses the challenges associated with engineering the total ship as part of the joint warfare system from two important aspects, the

impact of differing design team perspectives and inherent system complexity.

THE SHIP AS PART OF A COMPLEX SYSTEM

A warship is just one part a total system that fits in a system and associated subsystems, or system-of-systems, context as part of the battlegroup, expanding to include interconnectivity with a joint force structure (Hockberger 1996). The complexity associated with the engineering of warship concepts is observed when considering the multiplicity of functions desired and the large number of physical subsystems and parts. The fact that the system must be considered becomes obvious if one considers that inserting a single highly advanced warship as a node into an existing battlegroup, that interoperability cannot be obtained since the equipment processing and interconnective protocols are incompatible. The complexity shows up in the behavior of the networked ship system, however the behavior of interest emerges only after the system is actually integrated and operated. Such a large-scale complex system is difficult to analyze as a whole.

A useful tool to organize large-scale systems into manageable subsystems is decomposition. Using decomposition, a system can be broken down into any number of logical subsystems arranged in a hierarchy that defines the interconnections among the subsystems. The hierarchy maintains the structure of the system through subsystem interconnections. The hierarchy can be useful in studying the analysis of a large system, or can be used to study the working organization of the engineering teams performing a ship design. Any hierarchy created by decomposing a system depends on the perspective taken by the viewer, and subsequently any number of decomposed hierarchies can be defined for the same set of systems. When viewing a system, the designer defines a desired perspective, focussing on an aspect, then decomposes that aspect into subsystems in order to create a logical structure

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with bounded subsystems that can be more easily analyzed and engineered. A naval warship, for example, has hull, mechanical, and electrical (HM&E) systems for mobility, survivability, and habitability, a combat system to engage the enemy, and is an element of the warfare system. For each of these - HM&E, combat, warfare - the boundaries and interacting elements are different. They are, in fact, three distinct subsystems, all part of a decomposed system hierarchy with the HM&E and combat that can be defined as sublevel systems as shown in Figure 1. Currently, subsystems are commonly created for assignment to designers, with the system integration occurring only after each sublevel domain has done much design trade-off exclusive of considerations of the other, and without measuring of system effectiveness.

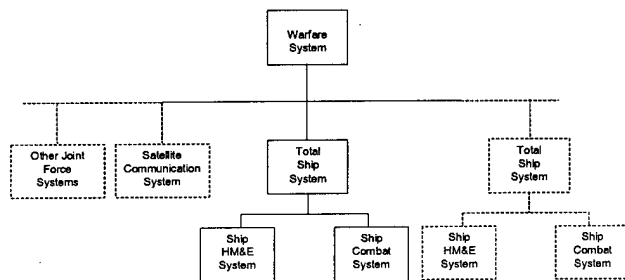


Figure 1. One Possible Warfare System Decomposition Hierarchy

THE WARFARE SYSTEM

TSSE, and the expansion of the traditional naval architectural focus on the ship hull, mechanical, and electrical systems, evolved beginning about the time of the first naval tactical data system (NTDS) installation on USS California and the AEGIS system design for the USS Ticonderoga in the 1970's. Combat system engineers have dealt with this aspect regularly since then, with new requirements driving the need for innovative technologies, and technologies continuing to change and improve rapidly according to Moore's Law. The basis on which mission effectiveness is measured is now much more concerned with the ethereal interconnections of data nodes and electromagnetic interconnections than with direct physical contact interactions arising from the ship interface with the natural environment. The interconnective electromagnetic properties are

just as real and physical, but their manifestations as system performers are harder to determine in the early stages of concept design. For example, the effectiveness of a network of nodes cannot be determined *a priori*, since the network behavior is an emergent system property.

Consider a naval warfare system, such as the battlegroup shown in Figure 2. Elements of a battlegroup include surface ships, submarines, aircraft, satellites, and many other joint assets. A battlegroup system when deployed at sea may cover a large area and some elements may be separated by many miles, and most may be over the horizon from any single ship perspective. The force appears as a group of independent physical objects. What are not shown are the communication links among the different battlegroup elements. These links provide tactical data and force orders so that there is connectivity among the different elements, or nodes, of the force. These communication links allow the individual nodes of the battlegroup to act in concert with one another. For many years these communications were limited to information passed from person-to-person, but now include data automatically passed from computer-to-computer.



Figure 2. Battlegroup Steaming in Formation

The physical equipment elements that facilitate battlegroup connectivity are the transmitters and receivers that support everything from voice links to automatic digital data links. There is also equipment for data processing, storage, and display. These elements are integrated on their respective ships and provide connectivity to other ships. In this way the physically independent

ships and other elements of the battlegroup are nodes that are integrated through networks to form a warfare system. Unlike the ship system elements, the warfare system elements are not permanently integrated during the design and development process. Shared data is derived from the data collected by individual force elements and from sources outside the battlegroup. The process of integrating the battlegroup to form a warfare system occurs as the force deploys, and exists while it is deployed, but vanishes when the deployment ends. This transitory nature of warfare systems offers a challenge to design. The challenge is not to verify that connectivity exists in the deployed force, but rather, the challenge is to verify the capability to maintain connectivity even before the force is designed.

Naval architects are just now beginning to face similar challenges within the ship system itself. For example, manning reduction is being aggressively pursued, and as personnel are removed, the functions traditionally performed by them must be automated. This requires incorporating automated machines as an integral part of the design, with due consideration of the ship function as a part of the warfare system. The naval architect maps functions to the physical systems, requiring allocation to either automated machines or personnel. To accomplish automation, computer networks integrate the system elements by automatically collecting and processing data so when functionally integrated, the HM&E and combat system is a computer automated man-made machine with self-operating characteristics. These self-operating characteristics are difficult for the naval architect to model without considering the entire system in a dynamic sense during the design process.

WARFARE SYSTEM BEHAVIOR

The behavior of networked warfare systems can be readily defined in the context of what has become known as complex adaptive systems (CAS) (Holland 1995). For example, consider any large city.

"Buyers, sellers, administrations, streets, bridges, and buildings make up the physical parts of the city. These are not static parts, they are always changing, so that a city's coherence is somehow imposed on a perpetual flux of people and structures. No single constituent remains in place, but the city persists. What enables cities to retain their coherence despite continual disruptions and a lack of central planning?"

Similarly, a networked battlegroup's coherence, or persistence, depends on extensive interactions, the aggregation of diverse elements, and adaptation to environmental change. In broad terms that relate to the fields of economics, biology, and many other areas, CAS are, without exception, made up of large numbers of active elements that are diverse in both form and capability.

With reference to CAS, the coherence of a warfare system is best viewed as a set of interacting agents, or nodes, with interaction described in terms of rules or protocols. As nodes perform together, they define a behavior not based just on their individual characteristics, but from the aggregation of their combined interaction. Aggregation has been identified as a basic characteristic of all CAS, and the emergent phenomena that result is the most applicable aspect for understanding the warfare system. Emergence defines the complex large-scale behaviors resulting from the aggregate interactions of subsystem nodes. Emergent behavior manifests itself in complex temporal patterns. This emergent behavior is the product of progressive adaptation to changing inputs and outputs due to the flow of information through the warfare system. Flows over a network of nodes and connectors can be defined in terms of triads, (node, connector, resource) that for a warfare system consist of (computer systems, electromagnetic links, combat information). In general terms, the nodes are processors and the connectors designate the possible interactions. In CAS the flows through these networks vary over time, creating a temporally dynamic system. Nodes and connections can appear and disappear

as the computer systems adapt or fail to adapt, yet the battlegroup must remain as a coherent entity. Thus neither the flows nor the networks are fixed in time. The warfare system can now be defined not just by the physical elements, but by the coherence of the overall function, and the emergent behavior manifested by patterns that reflect changing adaptations as time elapses and information accumulates.

When the warfare system is viewed this way, the main engineering goal becomes one of defining system coherence rather than just the elements of the battlegroup, and designing to ensure required coherent functions are achieved. This becomes challenging in the face of the fact that the major factor in determining the effectiveness is based on emergent behavior that cannot be defined until the system is built and deployed, or until a theoretical framework for determining the emergent behavior can be put forward.

It is difficult enough that we must now deal with the design and engineering of a CAS, but we must also deal with a diverse set of engineers that define their own world in which to accomplish their goal of designing this system. In order to provide some way to mitigate the challenges associated with engineering the warfare system, the overall ship design process characteristics are presented. The two views of the design process are presented, followed by a comparison of the two views in an attempt to create a framework that can be used to define a single, common method with which to view warfare system engineering.

WARFARE SYSTEM DESIGN PROCESS OVERVIEW

In basic terms, design can be defined as a process to determine form based on function. Concepts are engineered as physical objects that map function to form. For most familiar objects, this is a fairly straightforward process; one that all engineers are familiar with inside their own specialty, such as mechanical or electrical engineering, for instance. Warship design teams, however, must not only address the factors common to all seagoing vessels such as hull form,

propulsion, and maneuverability, but also the choice and placement of command, control, communications, computers, intelligence, surveillance, and reconnaissance (C⁴ISR) and weapons systems, including their sensors, processors, and actuators. The ship system is generally characterized using two domains in which the design is accomplished. One domain is associated with the subsystem that is designed to operate on the water, broadly labeled here as naval architecture. This domain includes the ship and HM&E systems. The other domain is the subsystem that is designed to carry out the combat capability, broadly labeled here as combat systems engineering. This domain includes the weapons and C⁴ISR systems. These two subdomains in the combat systems engineering domain use distinctly different engineers, however, their design process thinking is similar, so they are grouped together. Although the naval architecture and combat system domains are not disjoint, they are often treated as such in practice, with engineers and design teams working in their own domain. Each domain can be successfully considered independently, as long as the interconnection dependence between them, and any relationships to the other subsystems in the hierarchy, is taken into account.

THE SHIP SYSTEM

Naval architecture and marine engineering are the traditional disciplines associated with defining the design of ship hull, mechanical, and electrical systems. Recently, naval engineering and TSSE have taken the place of naval architecture to broaden the engineering toward the naval warship system. These engineering disciplines include the consideration of combat systems as part of the design process, though not necessarily to the same level that combat system engineers would in their designs. For purposes of this discussion, however, the identifier 'naval architecture' will be used to represent the TSSE ship designer's point of view. For the naval architect, combat systems are treated as fixed inputs to the ship design, so that interfacing physical parameters such as weight, volume, centers of gravity, arcs of fire, electromagnetic radiation interference, and sensor coverage ensure a properly designed physical

total ship system. The naval architect's view of ship system design consists of a process that is traditionally viewed as a highly coupled collection of interrelated physical attributes. For instance, the selection of a power level for ship propulsion requires knowledge of the resistance of the ship hull. The ship hull geometry cannot be fully determined until the entire weight and volume required to be carried, including that of the propulsion system, is known. The same is true of many other physical aspects of the design as they directly impact other physical aspects. Therefore, once one aspect is fully developed, it often requires modification based on its relationship with other functionally unrelated parameters. This philosophy is extensively discussed in the literature, as an iterative process commonly referred to as "The Design Spiral" (Evans 1959). Since its introduction, several variations have been developed. The spiral itself is consistent between all variations, but the "spokes" defining each aspect of the design differs somewhat from version to version, Figure 3.

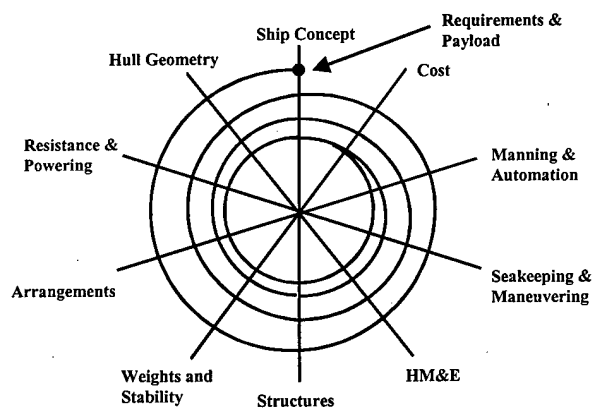


Figure 3. MIT Design Spiral

The spiral's spokes represent the set of all major areas that must be addressed throughout the design process to completely define the ship. The spiral itself depicts the current practice of independently developing each required parameter in a sequential manner, evaluating the relationship between design attributes, iterating to resolve conflicts, and repeating the evaluation/iteration process until all conflicts are

resolved. Thus, following each successive iteration, the design progresses closer and closer to the spiral's center until convergence is attained at a constant radius from the center.

Methods to expand the usefulness of the design spiral have been developed. The factor of time was added to the model (Andrews 1981). The essential concept remains the same, but the visual representation moved into three dimensions, with the added third dimension representing time. Figure 4 is the resulting cone shaped model. The design progresses through time by "cork-screwing" down the cone following a helical path. A cross section of the cone, essentially a spiral, represents a snapshot of the design process at a given instance. Design convergence is achieved at the cone's apex.

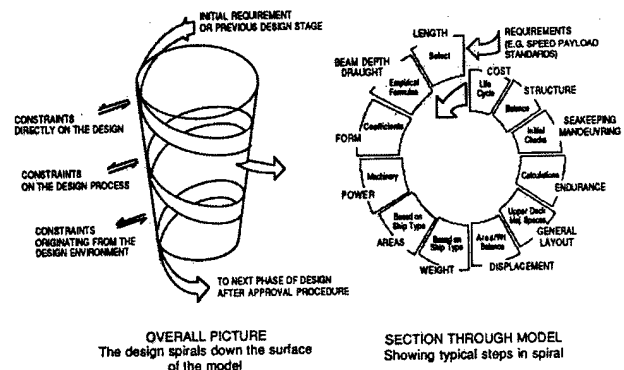


Figure 4. Enhanced Design Spiral (Andrews 1981)

Limitations of the spiral method description have been recognized, specifically, the inadequate addressing of concurrent engineering practices and life cycle concerns. One proposed solution to remedy these shortfalls is Decision-Based Design for the design of ships (Mistree, et al. 1990). This method divides the design process into subproblems that are solved in hierarchical order. The primary challenge to implementing this method is to define the hierarchical decomposition of the design process subproblems. No rigorous and generalizable methods are defined as part of this implementation.

More recent discussions view the ship design process as a combination of non-hierarchical and hierarchical subproblems interacting in ways that

are difficult to define and therefore nearly impossible to implement in practice (Brown 1993). The concept of decomposing the process seems the best way to accomplish ship design, but there is no currently defined method to do this, with coordination of the decomposed process becoming the major challenge.

With due consideration of the attempts to model and implement newer design methods, naval architecture remains a well developed discipline that uses theories principally derived from physical laws of fluid mechanics and strength of materials to design most aspects of the ship, such as the ship hull structure, *et cetera* (Gillmer and Johnson 1982). As an illustration, consider ship stability. The ship can be successfully modeled as a self-propelled semi-rigid body that is supported by a fluid and moves with six degrees of freedom. To be stable it will have an upright afloat position that exhibits stable equilibrium. In other words, it returns to its original position when heeled by an external inclining force that is applied and subsequently removed. Conversely, a ship in unstable equilibrium does not return to its original position resulting in capsizing.

Stability of the ship is determined by applying basic physical laws. For example: Newton's laws will determine the center of gravity (G); Archimedes' principle will determine the buoyancy; and the physical hull form geometry will determine both the center of buoyancy (B) and the metacenter (M), the theoretical point about which the ship pivots when exposed to an external inclining force. Stability requires the metacenter to be above the center of gravity as shown in Figure 5. The location of the center of gravity will not change with ship motion, but the center of buoyancy will change as the displaced volume changes. The coupling between the force of gravity and the buoyant force will maintain stable equilibrium of the ship as it undergoes longitudinal and transverse motion relative to a horizontal plane. Not all naval engineering aspects can be so easily performed, as the emergent properties of seakeeping and survivability should illustrate.

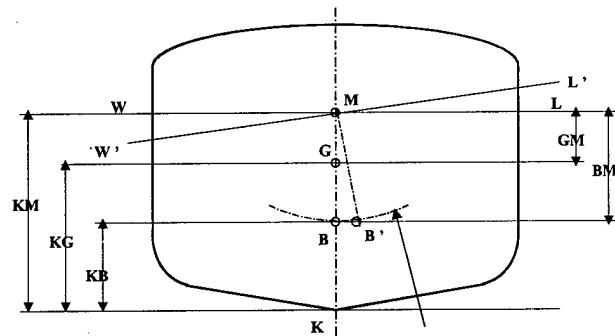


Figure 5. Transverse Metacentric Parameters

THE COMBAT SYSTEM

The combat system engineer's view is based on systems, and is tempered by the need to consider both a hard physical object and the more ethereal aspects of the design. In the combat system engineer's view, a system can be defined as a bounded set of interacting elements as shown in Figure 6. The system elements are physical objects, such as transmitters, receivers, and sensors, and they constitute a physical view of the system. For the elements to interact they will have some form of connection which can vary from direct physical contact to electromagnetic links. The boundary separates the system from the rest of the world, and it is at the boundary where inputs are given to the system and outputs are received from the system. The system has at least one input and at least one output, and the system function is defined by the relationship of the input to the output. For instance, if the system is a radar used to detect and track targets then the input would be detection and the output would be track. In general, a functional description of a system requires describing how each element contributes to converting input to output and how the different elements interact in accomplishing the conversion. A given system may be required to perform a set of functions, that is, there may be different kinds of inputs and multiple outputs. Designing and building a system requires integrating its elements in such a way that the internal behavior of each element, when coupled through the collective interaction of all elements, results in satisfying all the required system functions. The elements of multifunction systems will be time shared by the different functions.

Multifunction systems require complicated timing and control across all elements. Timing and control is not a required system function that converts input to output, rather it is a function that is required to integrate the system elements.

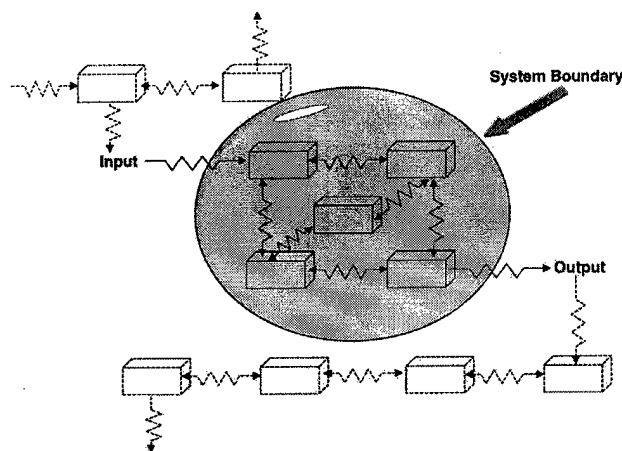


Figure 6. System as viewed by Combat System Engineers

Physical integration is the joining of elements to form a physically connected structure, such as a highway bridge or the hull of a ship. Functional integration involves joining elements to form a functionally connected structure, such as a group of ships acting as a battlegroup system by means of data exchanged over electromagnetic links. The elements of functionally integrated structures interact by means of input and output signals, whereas the elements of physically integrated structures interact by direct contact. Warships are elements, though systems in themselves, that are integrated both physically and functionally. The evaluation of these two aspects for design requirement adequacy is quite different depending on whether the functional or physical characteristics are being verified. Traditional test and evaluation methods are readily applied to the physical characteristics, but are less adaptable for establishing functional characteristics. The combat system engineering process for design and integration may be summarized in general as follows:

- System functions, i.e., input-output pairs, defined
- Physical elements identified

- System functions subdivided and allocated to various physical elements
- Physical elements designed, built, integrated, and tested

The process is iterative, all the steps are repeated until a design solution can be found such that all the elements interact properly to transform input to the desired output. One reason the process is iterative is that integration requires interfaces between the individual elements. Each interface will need an output from one element to be input to another. Each output-input, or input-output, requires an element-to-element function as a consequence of system integration. The existence of these integration functions - including timing and control of all elements-means that decomposing system functions into sub-functions to be allocated to elements cannot be arbitrary and is frequently non-linear. The required functions may always be mathematically decomposed into sub-functions that add by linear superposition. When these sub-functions are allocated to elements they will combine with the integration functions and the sum will represent the actual system.

A warship is outfitted with a combat system, that is, sensors and weapons capable of detecting and engaging air, surface, and subsurface targets. An example of a combat system is shown in Figure 7. Elements of the combat system - sensors, weapons, and man-machine interfaces - are integrated functionally with each other. They are also integrated physically with HM&E as part of the ship structure. Physically, the combat system is described by mathematics based on physical laws similar to the way HM&E is described. Functionally, the combat system is integrated independent of HM&E, so that functionally it is not part of the ship structure.

Functional integration is matured by a heuristic approach that includes test and evaluation as an integral part of the process. The functional design can be done independent of the physical ship structure. However, the physical and electrical design and integration is done as part of the HM&E. The combat system is an integral part of the space, weight, and power consumption of the

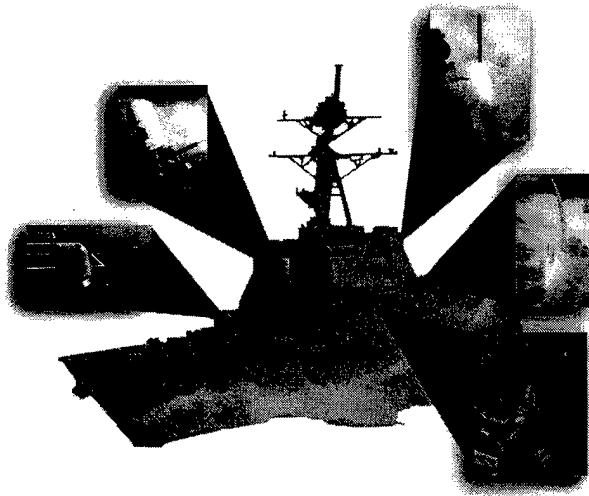


Figure 7. Combat System

ship, but it also has specified functional characteristics that are independent of that structure.

GENERAL OBSERVATIONS

The engineering process for warfare systems, composed of ship HM&E and combat systems, differ, but must be considered in an integrated fashion. The characteristics are not the same within each domain, so each has evolved its own approach based on the nature of the problems. The traditional approach to naval architecture in engineering a total ship is based in large part on the physics associated with objects based on traditional theoretical knowledge. The approach for the combat system, and likewise the warfare system, is to rely on a more heuristic approach, mainly due to the need to design for emergent behavior that is currently not founded on a well defined theoretical basis. The differences are subtle, but they have an impact on the ability to engineer the total ship.

Each domain defines and uses the term "function" differently. To the naval architect, a function is a use to which a form is put. To the combat system engineer, a function is a term used to define the use of an element, module, or subsystem, more in terms of a transform of input to output. Functional integration (combat system engineer usage) is driven by computer automation that has continued to grow in scope of application and

now includes automating the battlegroup to form a warfare system. This difference causes more than just communication problems between the domain engineers.

Both domains use an iterative process. Iteration necessarily dictates the modification of each parameter conflicting with one or more other parameters until agreement in all aspects is reached. Therefore, the final synthesized design is a variation of the designer's vision often arrived upon using trial-and-error methods. This process is rarely accomplished in the same sequential manner, making it *ad hoc*. The iterative nature makes it difficult for the domains to work concurrently, since there is tight coupling between the two domains.

Complexity associated with the emergent behaviors poses a similar challenge to both domains. The physical subsystems of the warfare system, for example the welding of a ship hull, the calibration of an electronics console, or the stability of a hull form, can be tested by straightforward means. The automated computer network control system or the networked battlegroup interconnectivity emergent behavior presents a challenge since the complete system exists only when the battlegroup is deployed at sea.

Until recently, the method of "build a little, test a little, learn a lot" (Meyer) expressed the fact that characteristics associated with complex interconnected systems had to be established by small steps of educated linear extrapolation from known behaviors, trial and error testing, and evaluation of results. Each step had to be large enough to be significant, but intentionally kept small enough to manage risk.

Today, engineers must be even more concerned with the links that connect systems, rather than just the systems themselves. Warfare systems are tested using actual equipment located at dispersed land based sites in conjunction with sea-based platforms. For example, the following land-based test sites can be connected to evaluate functionality: a DD-963 in Dam Neck, VA, an Aegis cruiser in Morristown, NJ, and Aegis destroyer in Dahlgren, VA, a CV in Pt. Loma,

CA, and an E-2C in Pt. Magu, CA. These systems are connected through T-1 and other high speed data links to simulate battlegroup interoperability. These sites are also connected to ships at sea to expand the test to the operational environment. A "D minus 30" process is implemented to start the process of battlegroup configuration at 30 months prior to deployment. During the 30 months, new system components are installed and tested, configuration controlled, and eventually deployed with confidence that the overall system will work. The overall engineering process is one of system integration where elements and subsystems are integrated bit-by-bit to form the complete warship system. These approaches and others are currently being used to engineer warfare systems, but rapid technology development change causes great challenges in the ability to keep the latest capability deployed over the entire warfare system. The consideration of these aspects poses both a theoretical and a practical challenge.

THE THEORETICAL CHALLENGE

The theoretical challenge is defining the warfare system in terms of functional coherence, since all battlegroups are neither identical in terms of specific elements and number of elements nor in the temporal make-up of the force during the mission. For the ship system, the subsystems used to provide connectivity may vary from element-to-element as new ones are introduced and older ones retired. For the temporal aspect, during deployments some ships may be reassigned causing connectivity changes and hence changes to the system coherence.

Until an actual deployment occurs, the warfare system cannot be completely defined in terms of its boundaries, its nodes, or the interaction of its networked components. Complexity theory is not mature enough to be applied to the engineering of system emergent behavior. Until complexity theory, or some related one, applies to warfare system engineering, challenges will continue to confront engineers, since construction of full-scale prototype warships and interconnected battlegroups for the purpose of evaluation is not practical.

THE PRACTICAL CHALLENGE

The practical challenge is to define a design methodology that allows both naval architects and combat system engineers to perform design using a method that formalizes design semantics and maintains the decomposed subsystem interconnections. A generalized method for implementing design that allows mapping of function to form while eliminating, or at least bounding, iteration would assist in creating an environment for the domains to work independently while achieving an integrated system. Determining iterative coupling allows design teams to work independently, with the subsystem couplings defining the context for cross team interactions at the interfaces. Such a generalized method has been defined, and is proposed as a framework for redefining the process of engineering warfare systems. The method is neutral, and does not advocate a need to train engineers as designers in all areas, but allows domain specific engineering with due consideration of coupling interfaces. The method is based on the axiomatic approach to design (AAD) (Suh 1990 and 2000).

AXIOMATIC APPROACH TO DESIGN

The ultimate goal of axiomatic design is the formulation of scientific-based, non-iterative design solutions. Pure axiomatic design takes place in a "solution neutral" environment. It is often difficult for the designer to remain completely "solution neutral" because all existing design solutions must necessarily be disregarded. The goal is to explore the feasibility of using axiomatic design principles to define an efficient way to structure the system design process. The foundation of axiomatic design is two axioms: the Independence Axiom and the Information Axiom. The Information Axiom is neither discussed, nor utilized in this paper.

The axiomatic approach to design decomposes the process into four separate domains, the customer domain, the functional domain, the physical domain, and the process domain. A specified

vector type characterizes each domain as shown in Figure 8. Mapping enables the designer to logically progress through the design process by first determining **what** is required in each domain, and then specifying **how** these requirements are satisfied in the next successive domain. Mapping between the domains is done using design matrices. The entire process advances by “zigzagging” between adjacent domains, thereby producing a hierarchical decomposition as the design is defined in increasing detail.

The axiomatic design principles have previously been outlined as a naval ship design process framework (Brown and Thomas 1998). The domains are tailored to reflect concept level ship design with the customer domain referred to as the mission domain. This framework provides the basis for both naval architects and combat system engineers to define a single design process.

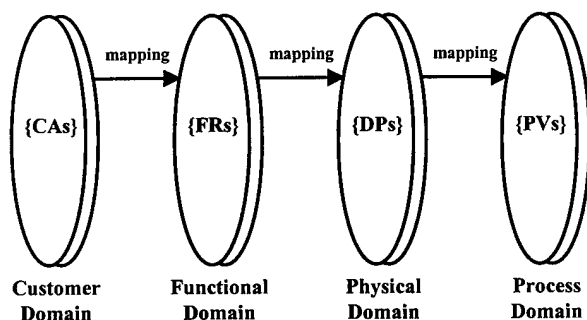


Figure 8. Design Domains including Characteristic Vectors

The Role of the Customer Domain and the Process Domain

The formulation of specific customer requirements begins with the exploratory mission analysis process. The key result of such an exploration is a detailed Mission Needs Statement (MNS) which outlines all facets of the mission that must be accomplished. The accomplishment of the stated mission is the reason for beginning the conceptual design process. Both naval architects and combat system engineers should be designing to the MNS.

When viewing the design process in this mission driven context, the customer domain may also be called the mission domain. Once the mission requirements are clearly defined, an analysis of alternatives (AOA) determines the best means of performing the mission. Therefore, the MNS is the primary means to determine the customer attributes (CAs) requiring mapping into the functional domain. In turn, the CAs determine the functional requirements (FRs) and the overall constraints placed on the design process. Constraints limit the designer’s available choices of design parameters (DPs). Figure 9 illustrates the progression from initial exploratory mission analysis to conceptual physical design.

The current practice used to evaluate the effectiveness of a naval combatant is based on its ability to carry out the specific missions it was

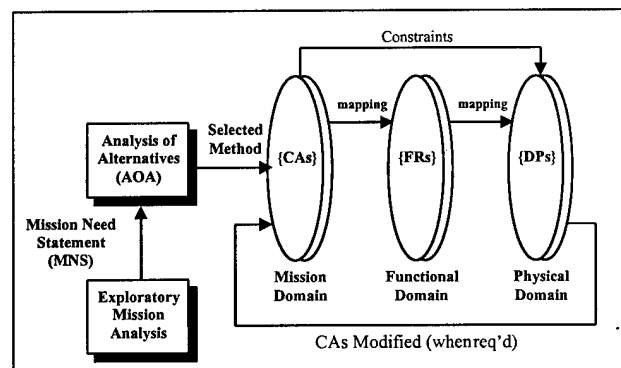


Figure 9. Mission Driven Design Progression

designed to accomplish according to the MNS. Therefore, effectiveness is measured in a context where the ship itself is viewed as a component, for instance during carrier battlegroup or amphibious operations, of a system. Typically, trade-off studies are conducted to determine the optimum combination of physical attributes (weapons payload, propulsion plant type, storage capacity, etc.). These studies solidify the customer attributes.

In the axiomatic approach to design framework, effectiveness of a design is based on its ability to satisfy the specified functional requirements. Once the best conceptual design is determined in

the system framework, the customer attributes are mapped into the functional domain. Upon entering the functional domain, axiomatic design is the method used to ensure maximum mission effectiveness.

Formal mapping from the customer domain into the functional domain is challenging for naval systems. Formal mapping of CAs into FRs is often difficult because the customer is often unable to precisely outline the desired specifications. For this reason, after a physical conceptual design materializes it must be presented to the customer. If the proposed design does not meet the expected performance, the CAs are modified causing the design goals to be re-defined. Figure 9 also illustrates this phenomenon.

By use of a design matrix, design parameters (DPs) in the physical domain are fulfilled by process variables (PVs) in the process domain. Process variables are the production and manufacturing resources needed to physically construct the required design parameters. In the context of ship design, the production tools and techniques used to construct each portion of the ship comprise the possible PVs.

Mapping from the Functional Domain to the Physical Domain and Design Decomposition

Considering the functional domain as including both naval architecture and combat systems functions, the AAD integrates the design process. The design questions become, "what functional requirements (FRs) must be provided" and "how is each specified requirement fulfilled by use of design parameters (DPs)." Equation 1 expresses the design process in vector format. Equation 2 represents the individual equations comprising the design process. The entire analysis is accomplished by "zigzagging" between these two domains, as the design is refined through decomposition.

$$\{FR\} = [A]\{DP\} \quad (1)$$

$\{FR\}$ = functional requirement vector
 $\{DP\}$ = design parameter vector
 $[A]$ = design matrix

$$FR_i = \sum_j A_{ij} DP_j \quad (2)$$

When following standard practice to initially evaluate a design, X 's and O 's populate all design matrix elements A_{ij} . These symbols represent the interaction between FRs and DPs. An X in position ij signifies DP_j effects FR_i . Similarly, an O in position ij signifies DP_j does not effect FR_i . Equation 3 provides the mathematical definition of the design matrix elements.

$$A_{ij} = \partial FR_i / \partial DP_j \quad (3)$$

If DP_j never changes in such a way as to influence FR_i , A_{ij} is represented by an O . A_{ij} may be either constant or varying throughout the design space. If A_{ij} is not a constant value, it must be evaluated at specific design points in the physical domain. Additionally, FR_i does not always vary linearly with DP_j . In these cases, as DP_j changes, the value of FR_i either increases or decreases in a nonlinear manner. Therefore, A_{ij} varies with both FR_i and DP_j .

Equation 4 shows an arbitrary functional to physical domain mapping applying these definitions. Equations 5 list these sample design equations in simultaneous equation format for further clarification. Note that all X 's are replaced by their respective matrix element designation in the simultaneous equations. For detailed analysis, the initial design equations characterized by X 's and O 's are updated at the appropriate level of decomposition by replacing each X with a quantifiable engineering expression.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ \vdots \\ FR_i \end{Bmatrix} = \begin{bmatrix} X & O & X & \dots & O \\ X & X & O & \dots & O \\ X & X & X & \dots & O \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X & X & X & \dots & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ \vdots \\ DP_j \end{Bmatrix} \quad (4)$$

$$FR_1 = A_{11}DP_1 + A_{13}DP_3 + \dots \quad (5)$$

$$FR_2 = A_{21}DP_1 + A_{22}DP_2 + \dots$$

$$FR_3 = A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3 + \dots$$

$$FR_i = A_{i1}DP_1 + A_{i2}DP_2 + A_{i3}DP_3 + \dots + A_{ij}DP_j$$

The “zigzagging” process enables the designer to logically decompose the design, thereby developing FR and DP hierarchies. Figure 10 illustrates this process. First, the designer selects a DP to satisfy a particular FR. Then a determination regarding further decomposition is made. If the selected DP is a well-established component or system that does not require re-design, the decomposition stops. For example, a naval architect seldom designs the prime mover that propels the ship. Instead, the appropriate engine is selected from an existing marine propulsion database. In this case, decomposition ceases once the naval architect selects the desired engine type.

On the other hand, if the chosen DP is not a well understood legacy component or system, decomposition is required. The designer decomposes the DP by determining the FRs it fulfills. Then, each of these FRs is satisfied with a suitable DP. Once again, a determination regarding the status of the lower level DP decomposition is made using the stated criteria. The designer “zigzags” between the two domains in this fashion until all the lowest level DPs do not require re-design. This lowest level of decomposition is referred to as the *leaf level*. The DPs at this level are called *leaf nodes*.

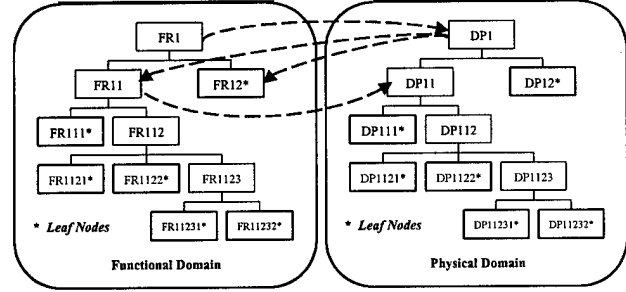


Figure 10. “Zigzagging” between Domains

The standard practice of tracking the design hierarchy is to use a numerical accounting scheme. Each highest level, or parent, FR/DP pair is given a sequentially increasing number designation (1, 2, 3, ...). At the next level of decomposition, the first child level, a sequentially increasing number is added to the right of the parent designation. For this paper, a decimal point separates these two fields (for example, 1.1, 1.2, 1.3, ... or 2.1, 2.2, 2.3, ...). If further decomposition is necessary, this procedure is again followed and a sequentially increasing number is added to the right of another decimal point (for example, 1.1.1, 1.1.2, 1.1.3, ...). In this manner, the design grows as *branches* until reaching the leaf level. The detail of each branch, that is the level of decomposition, varies depending on the DPs selected.

A good design maintains the independence of the functional requirements according to the Independence Axiom. According to axiomatic design theory, the design process does not continue to the next level of decomposition until the Independence Axiom is satisfied. It is this independence that allows subsystem to continue their designs in their own discipline, since interfaces have been accounted for in the decomposition. Independence is achieved by either an uncoupled or decoupled design. An uncoupled design is one in which only one DP satisfies each FR. A diagonal design matrix characterizes this type of design. A decoupled design is one in which the independence of functional requirements is satisfied if and only if the DPs are changed in the proper sequence. A triangular (upper or lower) design matrix characterizes this type of design.

A coupled design does not satisfy the Independence Axiom. This type of design signifies the need for iteration because successive DPs are not necessarily fixed as FRs are sequentially satisfied. In other words, a DP may require modification to satisfy one or more additional FRs. Once this modification occurs, the fulfillment of the original FR (in part by the subject DP) must again be verified. If fulfillment is not achieved the subject DP must once again be altered initiating the iteration process. A design matrix with elements populating both sides of the diagonal characterizes a coupled design.

Certain functional requirements of ships are inherently coupled (i.e., operate on surface of the water and move through the water). Therefore, developing a decoupled design is sought. A decoupled design allows the designer to concentrate all efforts in a logical sequence thereby eliminating the iteration process and allowing independent design. Once a portion of the design is complete, it theoretically does not require further modification upon completion of another aspect of the design.

The benefits of achieving a decoupled design are seen not only during the design process, but even after the design is complete. Technologies to improve the warfighting capabilities of modern naval surface combatants are continuously under development. This is especially true for applications involving computer microprocessing technology. Therefore, it is often desirable to install these new technologies onto the ship once they are fully developed. This can happen at any conceivable point throughout the ship's life cycle. A decoupled design allows the overall effect these new technologies have on other systems to be determined prior to insertion. Therefore, modifications enhancing the ship are less costly to implement at any stage of its operational life, including the ability to integrate new interoperability functions as new battlegroup configurations are required.

CONCLUSIONS

The battlegroup is a military force consisting of ships and other elements interconnected by

automated communication links, both within the ship and beyond, to create warfare system. A further complication is that links are established when the force deploys which means that the warfare system is integrated as a consequence of its existence and not as the end product of a construction process. The ability to design warfare systems for desired emergent behavior remains a challenge.

A warship is the result of a protracted and complex design and integration process that requires getting it right the first time. The warship can be built to a set of specifications that accomplishes physical integration, but the functional requirement hierarchy requires integrated consideration *a priori*. Building a prototype to test the engineering approach is not practical for large systems, so the Navy has established an alternative approach that relies on test and evaluation as a routine part of system integration. The construction of large complex systems is really an application of a process of defining independent functions and mapping them to physical design parameters to come up with design specifications.

Following present ship design methods using the two domains of naval architecture and combat systems, the modern warship is defined by multitudes of physical attributes. In order to achieve a design solution, many of these parameters must be designed multiple times, and ultimately compromised, using an iteration process. Using the axiomatic approach to design, these multitudes of physical attributes are reduced to small sets of functional requirements of the highest type simultaneously spanning both domains. These functional requirements are then satisfied by physical design parameters through a logical mapping process from the functional domain into the physical domain. Further decomposition of the FRs and their corresponding DPs, in tandem with "zigzagging" back and forth between the two domains creates a highly ordered, scientifically arrived at design solution. This concept solution-neutral approach allows designers to develop new and possibly innovative solutions to meet FRs in a cost-effective manner.

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